

Dark matter's X-files

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Sterile neutrinos with keV masses can constitute all or part of the cosmological dark matter. The electroweak-singlet fermions, which are usually introduced to explain the masses of active neutrinos, need not be heavier than the electroweak scale; if one of them has a keV-scale mass, it can be the dark-matter particle, and it can also explain the observed pulsar kicks. The relic sterile neutrinos could be produced by several different mechanisms. If they originate primarily from the Higgs decays at temperatures of the order of 100 GeV, the resulting dark matter is much “colder” than the warm dark matter produced in neutrino oscillations. The signature of this form of dark matter is the spectral line from the two-body decay, which can be detected by the X-ray telescopes. The same X-rays can have other observable manifestations, in particular, though their effects on the formation of the first stars.

1. Neutrino masses and the emergence of sterile neutrinos

Most discoveries in particle physics amount to either a measurement of some parameter related to a known particle, or a detection of some new degrees of freedom, new particles. The discovery of the neutrino mass¹ is both. Not only is it a measurement of the non-zero mass, but it also implies the existence of some additional, SU(2) singlet fermions, “right-handed” neutrinos. The corresponding particles can be made very heavy even for small masses of the active neutrinos (the seesaw mechanism²), but they can also be light, in which case they are called sterile neutrinos. The name *sterile neutrino* was coined by Bruno Pontecorvo, who hypothesized the existence of the right-handed neutrinos in a seminal paper,³ in which he also considered vacuum neutrino oscillations in the laboratory and in astrophysics, the lepton number violation, the neutrinoless double beta decay, some rare processes, such as $\mu \rightarrow e\gamma$, and several other questions that have dominated the neutrino physics for the next four decades. Most models of the neutrino masses introduce sterile (or right-handed) neutrinos to generate the masses of the ordinary neutrinos via the seesaw mechanism.² The

seesaw lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \bar{N}_a (i\gamma^\mu \partial_\mu) N_a - y_{\alpha a} H \bar{L}_\alpha N_a - \frac{M_a}{2} \bar{N}_a^c N_a + h.c., \quad (1)$$

where \mathcal{L}_{SM} is the lagrangian of the Standard Model, includes some number n of singlet neutrinos N_a ($a = 1, \dots, n$) with Yukawa couplings $y_{\alpha a}$. Here H is the Higgs doublet and L_α ($\alpha = e, \mu, \tau$) are the lepton doublets. Theoretical considerations do not constrain the number n of sterile neutrinos. In particular, there is no constraint based on the anomaly cancellation because the sterile fermions do not couple to the gauge fields. The experimental limits exist only for the larger mixing angles.⁴ To explain the neutrino masses inferred from the atmospheric and solar neutrino experiments, $n = 2$ singlets are sufficient,⁵ but a greater number is required if the lagrangian (1) is to explain the r-process nucleosynthesis,⁶ the pulsar kicks^{7,8} and the strength of the supernova explosion,^{9,10} as well as dark matter.^{11–15} The same particle can play an important role in the formation of the first stars¹⁸ and other astrophysical phenomena.¹⁹

The scale of the right-handed Majorana masses M_a is unknown; it can be much greater than the electroweak scale,² or it may be as low as a few eV.¹⁶ The seesaw mechanism² can explain the smallness of the neutrino masses in the presence of the Yukawa couplings of order one if the Majorana masses M_a are much larger than the electroweak scale. Indeed, in this case the masses of the lightest neutrinos are suppressed by the ratios $\langle H \rangle / M_a$. However, the origin of the Yukawa couplings remains unknown, and there is no experimental evidence to suggest that these couplings must be of order 1. In fact, the Yukawa couplings of the charged leptons are much smaller than 1. For example, the Yukawa coupling of the electron is as small as (10^{-6}).

The Majorana mass can arise from the Higgs mechanism.¹⁷ For example, let us consider the following modification of the lagrangian (1):

$$\mathcal{L} = \mathcal{L}_0 + \bar{N}_a (i\gamma^\mu \partial_\mu) N_a - y_{\alpha a} H \bar{L}_\alpha N_a - \frac{h_a}{2} S \bar{N}_a^c N_a + V(H, S) + h.c., \quad (2)$$

where \mathcal{L}_0 includes the gauge and kinetic terms of the Standard Model, H is the Higgs doublet, S is the real boson which is SU(2)-singlet, L_α ($\alpha = e, \mu, \tau$) are the lepton doublets, and N_a ($a = 1, \dots, n$) are the additional singlet neutrinos. After the symmetry breaking, the Higgs doublet and singlet fields each develop a VEV, $\langle H \rangle = v_0 = 247$ GeV, $\langle S \rangle = v_1$, and the singlet neutrinos acquire the Majorana masses $M_a = h_a v_1$. As discussed below, this model is suitable for generating dark matter in the form of sterile neutrinos.

2. Dark matter in the form of sterile neutrinos

Sterile neutrino is a dark matter candidate. Since the singlet fermions are introduced anyway to explain the observed neutrino masses, one can ask whether the same particles can be the dark matter. Because of the small Yukawa couplings, the keV sterile neutrinos are out of equilibrium at high temperatures. However, there are several ways in which the relic population of sterile neutrinos can be produced.

- Sterile neutrinos can be produced from neutrino oscillations as was proposed by Dodelson and Widrow (DW).¹¹ If the lepton asymmetry is negligible, this scenario appears to be in conflict with a combination of the X-ray bounds²¹ and the Lyman- α bounds,^{22,23} although it is possible to evade this constraint if the lepton asymmetry of the universe is greater than (10^{-3}) .¹³ On the other hand, observations of dwarf spheroids point to a non-negligible free-streaming length for dark matter,²⁴ which favors warm dark matter. It is also possible that the sterile neutrinos make up only a fraction of dark matter,²³ in which case they can still be responsible for the observed velocities of pulsars.^{7,20}
- The bulk of sterile neutrinos could be produced from decays of S bosons at temperatures above the S boson mass, $T \sim 100$ GeV.²⁰ In this case, the Lyman- α bounds on the sterile neutrino mass are considerably weaker than in the DW case because the momenta of the sterile neutrinos are red-shifted as the universe cools down from $T \sim 100$ GeV.
- Sterile neutrinos can be produced from their coupling to the inflaton,²⁵ or the radion.²⁶

It is important to note that only in the first case, the DW scenario, the dark matter abundance is directly related to the mixing angle. In contrast, if the relic population of sterile neutrinos arises from the Higgs decays, their abundance is determined by the coupling h in eq. (2), while the mixing angle is controlled by a different coupling y .

We also note that both models, with lagrangians (1) and (2), allow for some production of sterile neutrinos from oscillations, but in the case of the singlet Higgs decays (2) the bulk of the sterile dark matter could be produced at $T \sim 100$ GeV, regardless of the value of the mixing angle, which can be vanishingly small.

Indeed, if the couplings of S to H are large enough, while $h < 10^{-6}$, the S boson can be in equilibrium at temperatures above its mass, while

the sterile neutrino with a small mixing angle can be out of equilibrium at all times. Since S is in thermal equilibrium at high temperatures, some amount of sterile neutrinos can be produced in decays $S \rightarrow NN$:

$$\Omega_{\nu_s} = 0.2 \left(\frac{33}{\xi} \right) \left(\frac{h}{1.4 \times 10^{-8}} \right)^3 \left(\frac{\langle S \rangle}{\tilde{m}_S} \right), \quad (3)$$

where ξ is the change in the number density of sterile neutrinos relative to T^3 due to the dilution taking place as the universe cools. For example, in the Standard Model, the reduction in the number of effective degrees of freedom that occurs during the cooling from the temperature $T \sim 100$ GeV to a temperature 1 keV causes the entropy increase and the dilution of any species out of equilibrium by factor $\xi \approx 33$.

At the same time, the sterile neutrino mass is determined by the VEV of S :

$$h\langle S \rangle \sim \text{keV} \implies \langle S \rangle \sim \frac{\text{keV}}{h} \sim 10^2 \text{ GeV} \quad (4)$$

Based on the required values of Ω_s and the mass, we conclude that the Higgs singlet should have a VEV at the electroweak scale. The dark matter abundance, as in eq. (3), was first computed for a model in which the S field served as the inflaton with a potential adjusted to have $\langle S \rangle \gg m_S$, and much smaller values of h, ξ were considered.²⁵ The alternative possibility,²⁰ $\langle S \rangle \sim m_S$, which some may find more natural, places the singlet Higgs right at the electroweak scale, which has important implications for the LHC.²⁷

3. X-ray detection of relic sterile neutrinos

The relic sterile neutrinos can decay into the lighter neutrinos and an the X-ray photons,²⁸ which can be detected by the X-ray telescopes.²¹ The X-ray flux depends on the sterile neutrino abundance. If all the dark matter is made up of sterile neutrinos ($\Omega_s \approx 0.2$), then the limit on the mass and the mixing angle is given by the dashed line in Fig. 1. However, the interactions in the lagrangian (1) cannot produce such an $\Omega_s = 0.2$ population of the sterile neutrinos for the masses and mixing angles along this dashed line, unless the universe has a relatively large lepton asymmetry.¹³ If the lepton asymmetry is small, the interactions in eq. (1) can produce the relic sterile neutrinos via the neutrino oscillations off-resonance at some sub-GeV temperature.¹¹ This mechanism provides the lowest possible abundance (except for the low-temperature cosmologies, in which the universe is never reheated above a few MeV after inflation²⁹). The model-independent bound^{20,23} based on this scenario is shown as a solid (purple)

region in Fig. 1. It is based on the flux limit from X-ray observations²¹ and the state-of-the-art calculation of the sterile neutrino production by oscillations.³⁰

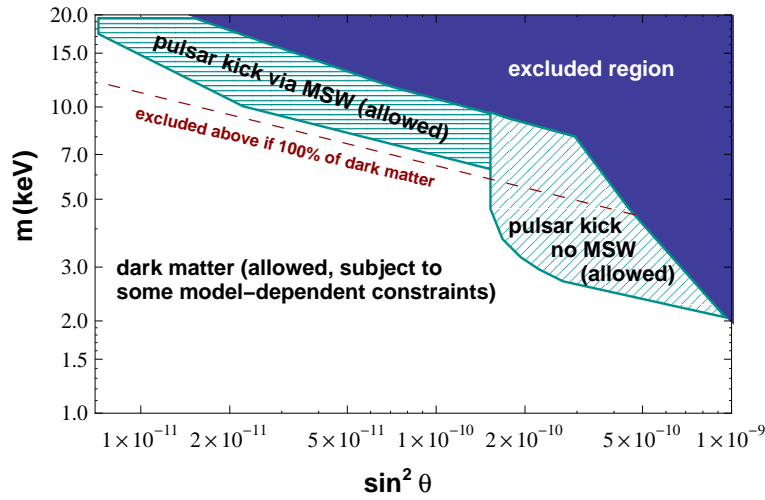


Fig. 1. The solid excluded region is based on a combination of the X-ray and the small-scale structure bounds;²³ it applies even if sterile neutrinos constitute only a fraction of dark matter. The dashed line shows the X-ray bound under the assumption that sterile neutrinos make up all the dark matter. Additional bounds from structure formation may apply, depending on the free-streaming length, whose relation with the particle mass depends on the production scenario. The region for the pulsar kicks shown here is based on the re-analyses of the earlier results,⁷ which will be reported in an upcoming paper.

4. X-rays and the formation of the first stars

The X-ray photons from sterile neutrino decays in the early universe could have affected the star formation. Although these X-rays alone are not sufficient to reionize the universe, they can catalyze the production of molecular hydrogen and speed up the star formation,¹⁸ which, in turn, would cause the reionization. Molecular hydrogen is a very important cooling agent, necessary for the collapse of primordial gas clouds that gave birth to the first stars. The fraction of molecular hydrogen must exceed a certain minimal value for the star formation to begin.³¹ The reaction $H+H \rightarrow H_2 + \gamma$ is very

slow in comparison with the combination of reactions



which become possible if the hydrogen is ionized. Therefore, the ionization fraction determines the rate of molecular hydrogen production. If dark matter is made up of sterile neutrinos, their decays produce a sufficient flux of photons to increase the ionization fraction by as much as two orders of magnitude.¹⁸ This has a dramatic effect on the production of molecular hydrogen and the subsequent star formation.

Decays of the relic sterile neutrinos during the dark ages could produce an observable signature in the 21-cm background.³² It can be detected and studied by such instruments as the Low Frequency Array (LOFAR), the 21 Centimeter Array (21CMA), the Mileura Wide-field Array (MWA) and the Square Kilometer Array (SKA).

4.1. *Sterile neutrinos and the supernova*

Sterile neutrinos with masses below several MeV can be produced in the supernova explosion; they can play an important role in the nucleosynthesis,⁶ as well as in generating the supernova asymmetries and the pulsar kicks.⁷ Since the sterile neutrinos interact with nuclear matter very weakly, they can be very efficient at transporting the heat in the cooling proto-neutron star, altering the dynamics of the supernova.⁹ This could lead to an enhancement of the supernova explosion. An additional enhancement can come from the increase in convection in front of the neutron star propelled by the asymmetric emission of sterile neutrinos.¹⁰

4.1.1. *The pulsar kicks*

The observations of neutrinos from SN1987A constrain the amount of energy that the sterile neutrinos can take out of the supernova, but they are still consistent with the sterile neutrinos that carry away as much as a half of the total energy of the supernova. A more detailed analysis shows that the emission of sterile neutrinos from a cooling newly born neutron star is anisotropic due to the star's magnetic field.⁷ The anisotropy of this emission can result in a recoil velocity of the neutron star as high as $\sim 10^3 \text{ km/s}$. While both the active and the sterile neutrinos are produced with some anisotropy, the asymmetry in the amplitudes of active neutrinos is quickly washed out in multiple scatterings as these neutrinos diffuse out of the star

in the approximate thermal equilibrium.⁸ In contrast, the sterile neutrinos are emitted from the supernova with the asymmetry equal to their production asymmetry. Hence, they give the recoiling neutron star a momentum, large enough to explain the pulsar kicks for the neutrino emission anisotropy as small as a few per cent.⁷ This mechanism can be the explanation of the observed pulsar velocities. The range of masses and mixing angles required to explain the pulsar kicks is shown in Fig. 1.

The pulsar kick mechanism based on the sterile neutrino emission has several additional predictions:⁷

- the kick velocities were predicted to correlate with the axis of rotation;⁷ recently, this spin-kick correlation was confirmed by the observations³⁴
- the kick should last 10 to 15 seconds, while the protoneutron star is cooling by the emission of neutrinos, but the onset of the kick can be delayed by a few seconds, depending on the mass and mixing angles;⁷ this delayed kick can be tested using the observational data³⁵
- neutrino-driven kicks can deposit additional energy behind the supernova shock,^{9,10} and they are expected to produce asymmetric jets with the stronger jet pointing *in the same direction* as the neutron star velocity.¹⁰

5. Conclusions

The fundamental physics responsible for the neutrino masses is likely to involve some additional SU(2)-singlet fermions, or sterile neutrinos. The Majorana masses of these states can range from a few eV to some values well above the electroweak scale. A sterile neutrino with a keV mass is a viable dark matter candidate. One can discover the relic sterile neutrinos using the X-ray observations. The same neutrinos can be produced in the supernova explosions, and the anisotropy in their emission can explain the observed pulsar velocities. The X-rays from the sterile neutrino decays can play an important role in the production of molecular hydrogen, which is necessary for the formation of the first stars.

This work was supported in part by the DOE grant DE-FG03-91ER40662 and by the NASA ATP grants NAG 5-10842 and NAG 5-13399. The author appreciates the hospitality of Aspen Center for Physics, where part of this work was done.

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